AIRBORNE ALBEDO MEASUREMENTS OVER THE ROSS SEA, OCTOBER–NOVEMBER 1962

MARTIN C. PREDOEHL AND ANGELO F. SPANO

Atmospheric Analysis Laboratory, Environmental Science Services Administration, Washington, D.C.

ABSTRACT

During October and November 1962, ten flights were made over the Ross Sea to the north and east of McMurdo, Antarctica, in a Navy C–54Q aircraft fitted with up- and down-facing Eppley pyranometers and with a camera for taking overlapping photographs of the terrain below. From a flight level of 7,500 ft. albedos of the underlying ice types were obtained for various elevations of the sun above the horizon. A few measurements were made from altitudes lower than 7,500 ft. to determine the change of albedo in the vertical. Measurements were made during both clear and cloudy weather, but only those in clear weather or under a uniform overcast are considered reliable.

The albedo of old and new winter ice exhibited very little change with elevation of the sun between 10° and 30° above the horizon, the values ranging from 60 to 70 percent but chiefly grouping around 65 percent. Values over young ice ranged from 10 to 25 percent. An albedo of 72 percent was obtained over the Ross Ice Shelf with the sun at 30° above the horizon, and a value of 5 percent was obtained over open ocean with the sun above 40°. Albedos over winter ice and over young ice computed from RG–8 (red) filter data were approximately half those obtained with WG–7 (clear) filter data. From the measurements at intermediate altitudes albedos over pack ice measured with WG–7 filters showed a decrease of about 1.4 percent per 1,000-ft. increase in flight altitude, and albedos over winter ice measured with RG–8 filters showed a decrease of about 5 percent per 1,000-ft. increase in flight altitude.

1. INTRODUCTION

The temperature pattern observed during the first winter at the IGY South Pole (Amundsen-Scott) station closely followed the patterns observed at several Arctic and Antarctic coastal stations. These had come to be known as coreless or "kernlose" because of their lack of a definite midwinter minimum. Wexler [16] related this phenomenon observed at the South Pole to the changes in the sea-ice belt and the strong circumpolar vortex about Antarctica in winter.

The explanation put forth relates the kernlose temperature pattern to the sea-ice belt through a chain of factors. The kernlose pattern is viewed as a combination of two effects, first, the initial rapid cooling brought about by the removal of solar radiation, and second, the arresting of the rapid cooling by the influx of warmer air borne inland by storms along the coast. Promoting the storminess is the strong temperature contrast along the leading edge of the pack ice. Among the numerous and complex physical factors responsible for the contrast, perhaps most important are (a) storage and transport of heat by the ice-free ocean, (b) continued absorption of solar energy by the ocean surface, (c) increased insulation of the pack-ice surface from the heat beneath it, and (d) high albedo of the pack-ice surface. Although the warm air borne inland may occasionally reverse the normal cooling process, the storms eventually remain so far away from the continental center that little warm air reaches there. The relative flatness of the temperature curves testifies to the reservoir of heat available while the slow continued decline suggests that this source region is growing increasingly remote.

The preceding explanation of the influence of the sea-ice belt upon the temperature regime of Antarctica points up the importance of a study of those factors which contribute to the growth and decay of sea ice. Although the changes in the sea-ice belt are linked with oceanic factors, the principal changes take place in response to the changing solar radiation. Throughout the year the leading edge of the ice belt remains to some extent within the illumination of the sun, even when the sun is farthest north, and during the height of the Southern Hemisphere summer the solar radiation incident on the pack ice is very large. The albedos of the various types and concentrations of sea ice and their distributions must be known to incorporate these factors into a heat budget of this region. The present research endeavors to determine the albedos of the different types and concentrations of sea ice under various conditions.

2. FIELD INVESTIGATIONS

For use in an airborne ice and albedo survey four temperature-compensated, wide spectral band Eppley pyranometers were purchased in the summer of 1961. Radiation reaches the sensor elements of these pyranometers by passing through two hemispheres of precision-ground clear glass (Schott WG–7). The outer hemisphere is readily removable for replacement with ones of special spectral band transmissivities such as the deep red filter (Schott RG–8), two of which were purchased along with

the pyranometers. These pyranometers are described in [15] and by Marchgraber and Drummond [12]. The filters are described by Ångström and Drummond [1] and in [5]. When purchased the pyranometers were fitted with special leveling mounts to adapt them for use in a modified Navy P2V aircraft.

To measure and record the outputs from the upfacing and the downfacing pyranometers in the aircraft a digital voltmeter, capable of scanning successively 20 separate inputs and printing out its measurements on paper tape, was purchased. A preamplifier was included to increase the strength of the input signals. A camera system the Navy had installed in the P2V for cartographic mapping completed the ensemble of equipment for the albedo study.

In September 1961 a test flight by the specially equipped aircraft was made over the Middle Atlantic States from New Jersey to Lake Erie and return, running nearly parallel to a concurrent TIROS satellite track. The favorable results of this flight were reported by Hanson and Viebrock [8]. After this flight, some further adjustments in the calibration of the pyranometers were made. The aircraft and equipment departed for Antarctica in October 1961, but the aircraft and over half the persons aboard at the time were lost in a crash shortly after arrival. The albedo measuring equipment was not aboard at the time of the crash and thus remained available for the albedo survey.

During April 1962 a Navy C–54Q aircraft to be used primarily for search and rescue and logistic missions was selected for continuing the ice and albedo survey out of McMurdo, Antarctica. Modification of the C–54Q commenced at Norfolk, Va. Openings were cut in the top and bottom of the fuselage to permit the two pyranometers to protrude through the aircraft's skin. Each pyranometer, which could be leveled in flight by adjustment of spring-loaded screws through its baseplate, was held in place by four knurled-top bolts joining its baseplate to a specially constructed mounting frame. Cold air was kept out during flight by nonobstructive gaskets around the openings. Small hatch covers sealed these whenever the pyranometers were not in place.

The digital voltmeter with its accessories was strapped to a shock-cushioned tray atop a low metal table set into the floor of the aircraft along the right side of the aisle. The entire assembly was completely removable for cargo handling. In addition to the wires carrying the pyranometer output signals to the digital voltmeter, wires lead from the thermocouples imbedded in the bodies of the pyranometers for the purpose of providing a measure of instrument temperature, important for the proper interpretation of the results. An ice-water bath referenced the thermocouple outputs to 0° C.

For the albedo program the aircraft was refitted with a standard U.S. Navy CA–14(T–11) cartographic mapping camera having a 6-in. focal length and producing a 9 in. x 9 in. negative. To monitor the sequence and altitude of the photographs an instrument panel was installed immediately across the aisle from the digital
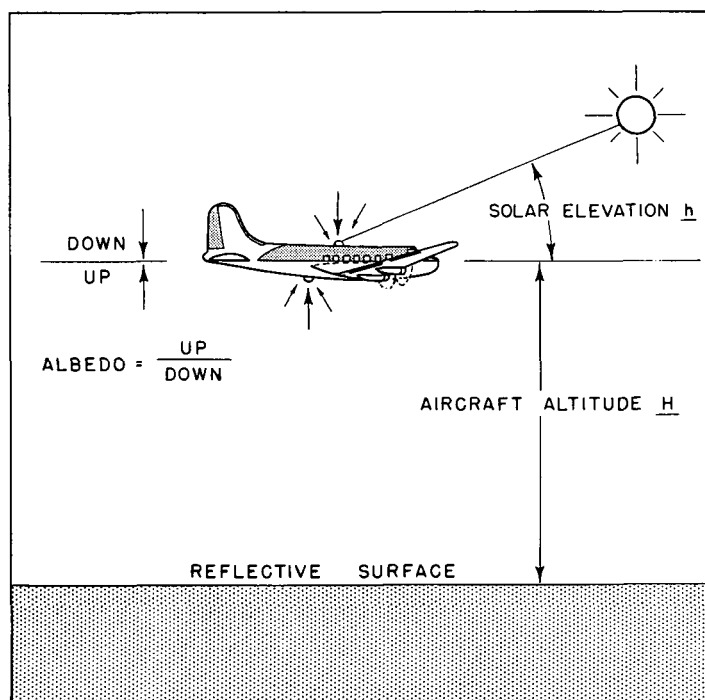

FIGURE 1.—A schematic representation of the pyranometer-equipped aircraft flying over a reflective surface at altitude H. The measured albedo is the ratio of the upcoming to the downcoming radiation and h is the solar elevation angle.

voltmeter. Just outboard of these installations bubble windows were installed for the combined benefit of the equipment operators and search and rescue missions.

Figure 1 shows a schematic of the C–54Q, equipped with upfacing and downfacing pyranometers, flying over a reflective surface. The figure also shows the parameters of aircraft altitude, H, solar elevation angle, h, and the representation of albedo as the ratio of the upcoming to the downcoming solar radiation over the reflective surface.

The modification of the C–54Q was completed in August 1962, and the equipment was tested under actual flight conditions on a flight made from the Naval Air Station, Quonset Point, R.I., on September 12, 1962. A problem later to be encountered in the Antarctic was the initial inoperativeness of the scanner-printer of the recording digital voltmeter. An albedo value of 3 percent was measured on this flight over open water with solar elevation angles of 52°–53°.

After arrival at McMurdo, Antarctica, we flew a total of ten albedo measurement flights over the western part of the Ross Sea from October 25 to November 24, 1962. The lines joining the circled points in figure 2 are the individual runs, those portions of the flights during which measurement were made. The logistics mission of the aircraft influenced the selection of flight tracks and altitudes to the extent that half of the albedo flights were made while transporting fuel and supplies to Hallett.
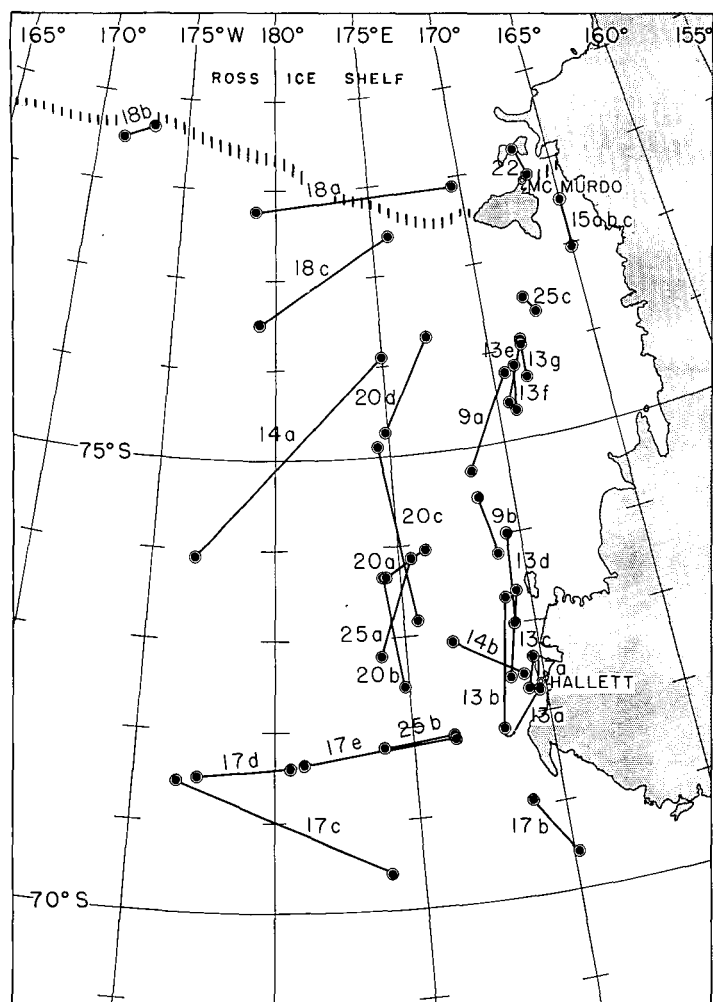
FIGURE 2.—Map of the western portion of the Ross Sea showing the albedo measurement runs. The runs, shown as the heavy lines connecting the circled points, are labeled in consecutive order as, for example, 13a, 13b, etc., from the flight of November 13, 1962.

The operation of the recording equipment was affected adversely by the extreme cold which made the printing mechanism very stiff. The risk of burning out drive-motor fuses or having highly erratic printing was always present. On most occasions fully an hour elapsed before normal operation could be expected. This problem was alleviated to a certain degree by preheating the printing mechanism with an aircraft reading lamp.

Greater difficulty was encountered in coordinating the photographic record with the printed tape record of the measured radiation. It was originally thought that by synchronizing our watches with the navigator's watch and the watch providing GMT time for each photograph we could adequately correlate the two records by noting times periodically on the tape. But because of the characteristic irregularity of the printout rate (as a result of the voltmeter's balance time being dependent upon the steadiness and magnitude of the input signal), time cor-

relation in this manner was not possible. We then turned to the method used, that of marking the printout tape every fifth photograph following an initial reference number. Since these marks occurred frequently and regularly, matching radiation measurements with photographic information between marks was very satisfactory. Also on the photographs appeared the pressure altitude of the aircraft, the frame number, and exposure data, all available for tie-in with the navigator's plot.

Most of the measurements were made over various concentrations of old winter ice, new winter ice, young ice, and open water. Other data were gathered over rarer types such as grease and slush ice. Scattered observations were made over the Ross Ice Shelf, moraine deposits in the vicinity of McMurdo, and pancake ice. On the return flight to New Zealand some measurements were made, purely for comparison purposes, over farmland, fields, and trees between Dunedin and Christchurch's Harewood Airport.

The flights were made between approximately 0100 and 0800 GMT, with the exception of the return trip to New Zealand during which measurements were made from approximately 1500 to 1600 GMT and 2230 to 0030 GMT. This range of times partly accounts for the wide range of solar elevation angles in the data. These angles ranged from approximately 6° to 35° for the Antarctic flights, with the preponderance of the data falling around 20°, and 3° and 54° on the flight back to New Zealand.

Flight altitude was normally maintained at 7,500 ft. It had previously been planned to have flights much higher than this, but serious limitations to the maximum altitude of the aircraft were imposed by a defective engine. In spite of this a special color photography flight over the dry valleys in the Royal Society Mountain Range was flown at 10,000 ft. for a short period of time; the rest of it was flown at altitudes from 6,500 to 5,000 ft. Three triple-level runs from two separate flights were flown at 7,500, 5,000, and 2,500 ft. in order to examine the change of albedo with altitude. The RG–8 red filters for the pyranometers were used on the third of these sets of three-level runs (the second of the two flights) and also on a flight at constant altitude of 7,500 ft.

In general, the flights were made with clear, or nearly clear, skies. However, it was not always possible to have these ideal conditions, and some flights were made with scattered or broken sky coverage. Whenever the clouds increased to the point of casting doubt on the representativeness of either the incoming or reflected radiation, the run was terminated. The prevailing types of clouds encountered were stratocumulus, altocumulus, cirrus, and cirrostratus, plus a few cumulus over open water.

3. ANALYSIS

The data gathered during the flights consisted of the outputs from the pyranometers and a reference value of potential printed on the recorder tape. As already
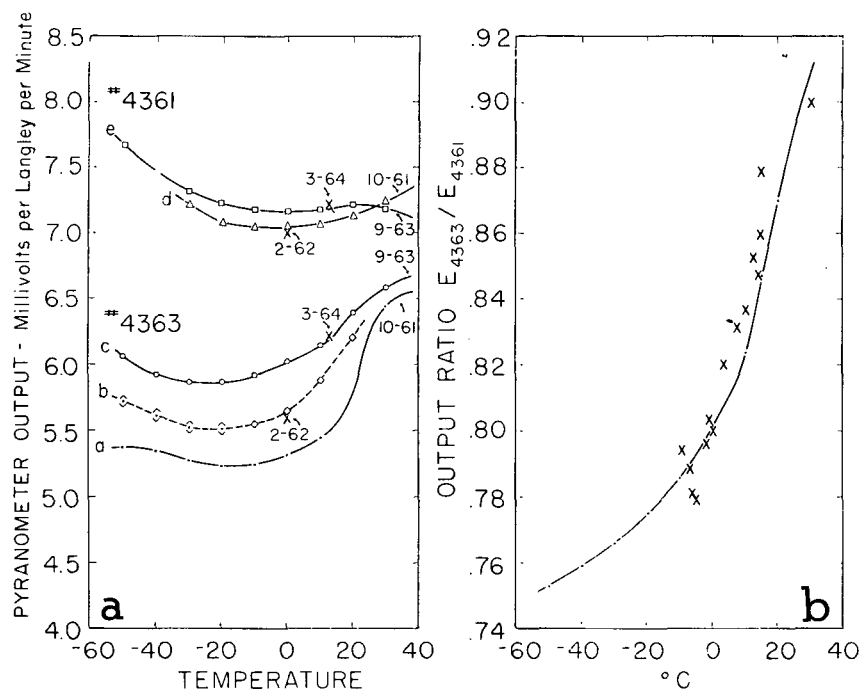
FIGURE 3.—(A) Pyranometer outputs in millivolts for a radiation input of one gm.-cal. cm.$^{-2}$ min.$^{-1}$ as a function of instrument temperature. Curve a: Pyranometer #4363 as calibrated by Eppley Laboratories, October 1961; Curve b: #4363 calibration based on comparisons with #4361, February 1962; Curve c: #4363 as calibrated by Eppley Laboratories, September 1963; Curve d: #4361 as calibrated by Eppley Laboratories, October 1961, and verified in February 1962. Curve e: #4361 as calibrated by Eppley Laboratories, September 1963. The crosses represent calibration checks performed during February 1962 and March 1964. Curves b and d were used in the reduction of the 1962 data. (B) The curve shows the ratio of the output of pyranometer #4363 to that of pyranometer #4361. The crosses represent comparison checks.

pointed out, the absence of a time reference or fixed interval between each printout required the placing of a mark on the data tapes when preselected numbered photographs were taken. The time of occurrence of each datum could be determined by interpolating between the times of these photographs. The observer's notes on surrounding weather conditions and the underlying surface also employed photograph numbers as a reference for coordination with the other data. Knowing the latitude, longitude, and time at the ends of the data runs made possible the computation of the solar elevation angle and the solar bearing angle at each of these points. After the end point data had been computed, values of the solar elevation angle, the solar bearing angle, latitude, and longitude were determined by interpolation each minute along the runs.

Determination of the calibration factors of the instruments employed, at various temperatures, had been one of the most important tasks of this project up until the time of the actual measurements. It was found following the first test flight that the temperatures reached by the lower instrument were lower than those for which calibrations were available; all four pyranometers were therefore calibrated a second time prior to the 1961 expedition. A cursory comparison check in McMurdo at that time revealed further cause for caution in the application of the supplied calibration factors. Therefore, following the return from the Antarctic, extensive comparison tests were made between the two instruments, #4361 and #4363, subsequently used in this project, to learn to the greatest extent their output values over a wide range of tempera-

ture. Figure 3A shows three calibration curves for pyranometer #4363 and two for pyranometer #4361. Curve b for #4363 and curve d for #4361 were employed for reducing the data gathered in the 1962 albedo measuring expedition. These two curves were derived from the past calibration history of the instruments, comparisons of their outputs when exposed to equal radiation input at a number of temperatures (fig. 3B), the output behavior of each instrument against its own output at some selected temperature as its temperature was varied in a cold chamber, and field calibration checks against a normal incidence pyrheliometer of established accuracy. From these calibration curves, tables of output conversion factor were generated for each value of thermocouple output within the encountered temperature range for each instrument. In analyzing the albedo data each pyranometer output value was converted to a sensed radiation value, assuming environmental equilibrium, and these values were then plotted in the order of their occurrence. Accompanying photograph numbers and notes on the visual observations were entered along with the plotted data.

In computing albedo values from the radiation values a running mean of five downcoming radiation values was used with a single instantaneous upcoming value in the ratio $A=U/D$ in order to obtain smoother and more accurate results. The recorded short-period variations in the downcoming radiation were not considered representative of the radiation illuminating the surface below, but the variations in the upcoming radiation were regarded as representative of changes in the surface below.

A very uniform surface below would tend to reveal irregularities in the upcoming radiation which would not be attributable to surface differences. The albedo values thus obtained were plotted along with their antecedent radiation values in the manner indicated at the end of the preceding paragraph.

As soon as prints had been obtained from the rolls of photographic negatives taken during the flights, the time shown in each one or each fifth one was recorded and plotted to the nearest tenth of a second against the picture number. Such plots provided the time for all events employing the picture numbers as reference. By selecting radiation and albedo data on the basis of the filter, altitude, cloud conditions, solar elevation angle, and ice type and amount, useful relationships could be deduced.

Figure 4 shows the albedo values determined over various types of ice, where these types could be found separately, with the solar elevation angle varying within the indicated range. Certain of the types have only a limited amount of data available for study. Considerable spread is evident in the display. Since old and new winter ice so frequently occur together figure 4C, contains this category which affords a series of measurements over a wider range of solar elevation angles than did the two separate categories, old winter ice (fig. 4A) and new winter ice (fig. 4B). Young ice occurrences (fig. 4D) were isolated, as indicated by the short range of solar elevation angles. It is widely encountered, however, between broken-up ice of earlier origin. Once young ice has acquired a snow cover it hardly differs in albedo from the surrounding older ice. When the ice is newly formed, it presents a very dark appearance, much like open water, but as it thickens it takes on an increasingly grayer and whiter appearance and accelerates its own increase in thickness. Even with a snow cover its distinctive fluted edges, where rafting (the sliding of one sheet of ice on another) has occurred, identify it. In thicker ice such junctions show up as ridges which cast long and dark shadows over the snow and ice terrain when the sun is low.

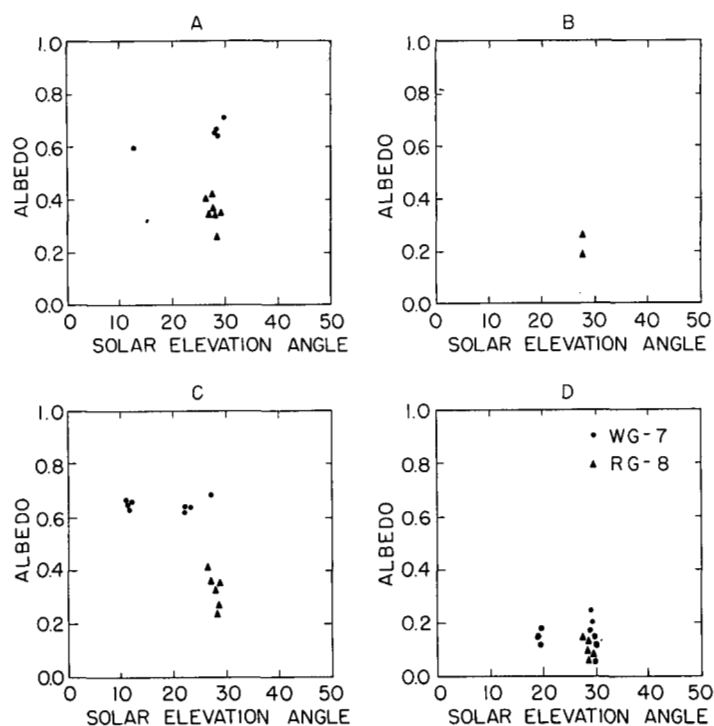In each of the above cases the RG–8 red filter measure-

FIGURE 4.—Measured albedo values over uniform ice fields with clear skies: (A) old winter ice; (B) new winter ice; (C) new and old winter ice; (D) young ice. The round dots indicate measurements made using the WG–7 or clear glass filters and the triangles indicate measurements made using the RG–8 or red glass filters.

ments indicate an albedo approximately one-half the WG–7 clear filter measurements. Table 1 summarizes these values, none of which has been corrected from its value at flight level.

The values in table 1 do not indicate a variation with solar elevation angle since no significant variations of this sort were found beyond a very slight indication of an increase of albedo measured over old winter ice with an increase in the elevation angle of the sun. Belov [3] reported that according to airborne measurements made by the Russians near Mirny in 1958, the albedo of the snow-covered Antarctic plateau increased slightly as the elevation angle of the sun increased. "Reddening" of the direct solar radiation at lower solar elevations and a decreased spectral reflectivity of fresh snow in the longer wavelengths, as well as the increase in ground shadows caused by sastrugi, were offered by Belov as an explanation for the findings. He reported sea-ice albedo values approximately the same as our values, but he found the albedo of snow with sastrugi slightly higher than our value for the Ross Ice Shelf. Additional measurements of the albedo over the polar plateau made with our equipment in a subsequent expedition are discussed by Spano [14].

From other sources we expected that the albedo values over snow surfaces would show increases with decreasing

TABLE 1.—*Albedos of various surfaces found in Antarctica from 7500 ft.*

Surface Description	Albedo	Filter	Spectral Band (μ)	Solar Elevation (deg.)
Old winter ice	0.64±0.05	WG–7	0.27–3.5	10–30
Old winter ice	.34± .08	RG–8	.69–3.5	25–30
New winter ice	.19– .26	RG–8	.69–3.5	25–30
Old and new winter ice	.65± .05	WG–7	.27–3.5	10–30
Old and new winter ice	.35± .09	RG–8	.69–3.5	25–30
Young ice	.15± .08	WG–7	.27–3.5	18–30
Young ice	.10± .04	RG–8	.69–3.5	28–29
Grease ice	.15± .03	WG–7	.27–3.5	25
Brash ice	.39	WG–7	.27–3.5	19
Pancake ice	.78	WG–7	.27–3.5	4
Ross Ice Shelf	.72	WG–7	.27–3.5	29
Stratocumulus undercast	.60– .85	WG–7	.27–3.5	18
Open water	.05	WG–7	.27–3.5	58

solar elevation angle. Liljequist [10] presents ample measurements over a snow surface with clear sky conditions which show that this takes place. He explains that when the sun is near the horizon the direct solar component on a horizontal surface becomes less than the diffuse sky component, and that since the latter is relatively richer in the shorter wavelength portion of the solar spectrum, to which snow has a higher reflectivity than to the longer wavelength portion, the overall albedo should be higher. He does, however, regard the presence of sastrugi as a reason for a decreased albedo with direct solar radiation, especially as compared with the albedo to be found under overcast conditions.

Lyubomirova [11] reported finding regular increases in the albedo of blocks of river ice as the effective elevation angle of the sun decreased. In the tests the blocks of ice were tilted on a test stand while being illuminated by direct solar radiation of essentially constant spectral composition. The reflected radiation was measured by means of a pyranometer mounted 20 cm. above the plane of the 1.8 m. diameter blocks. The formula

$$A(h) = A_0 - a \sin h + b \sin^2 h,$$

where $A(h)$ is the albedo at solar elevation angle h, A_0 is the albedo at $h=0°$, and a and b are constants to be evaluated separately for each type of surface, describes the relationship Lyubomirova found between the albedo and the solar elevation angle for the samples of ice tested. The same was said to apply to snow surfaces. The slope of the change of albedo with change of solar elevation angle determined by Liljequist at Maudheim agreed reasonably well with the slope of these changes in Lyubomirova's [11] report.

Although we began gathering our data with an awareness that the albedo measured at 7,500 ft. over sea ice would not in general be the same as the albedo measured at the surface, we did not know whether the value would increase, decrease, or remain about the same. We, therefore, planned to make albedo measurements at three equally spaced altitudes above several ice surfaces with the hope of determining the manner and extent of variations in the downcoming and upcoming components of solar radiation and in the albedo.

Accordingly, on a flight southward from Hallett to McMurdo, November 13, we flew over a selected stretch of ice at 2,500 ft. After a short period of time we turned and flew northward over essentially the same ice at 5,000 ft. Lastly we flew over the stretch of ice in the original direction at 7,500 ft. (Runs 13b, c, and d, fig. 2), each time obtaining WG-7 clear filter radiation measurements and photographs. A little farther along this same flight we repeated the same procedure, but reversed the order of the altitudes (Runs 13e, f, and g, fig. 2). On November 15 we made similar tri-level runs over a portion of McMurdo Sound making use of the RG-8 red filters on the pyranometers (Runs 15a, b, and c, fig. 2). The original

TABLE 2.—*Variation of radiation and albedo with flight altitude*

Date Filter	November 13, 1962 (#1) WG-7			November 13, 1962 (#2) WG-7			November 15, 1962 RG-8		
Altitude (ft.)	7,500	5,000	2,500	7,500	5,000	2,500	7,500	5,000	2,500
Pressure (mb.)	714	796	887	714	796	887	714	796	887
Downcoming Rad. (Meas.) *(ly. min.⁻¹)	0.684	0.748	0.805	0.568	0.562	0.480	0.485	0.457	0.413
Upcoming Rad. (Meas.) (ly. min.⁻¹)	0.375	0.416	0.456	0.298	0.335	0.278	0.167	0.177	0.174
Albedo	0.548	0.557	0.567	0.524	0.596	0.580	0.345	0.387	0.422
Solar Elev. Angle (computed)	24°12'	26°15'	28°21'	20°41'	19°48'	18°57'	28°20'	27°20'	26°27'
Solar Elev. Angle (adjusted)	26°18'	26°18'	26°18'	19°53'	19°53'	19°53'	26°18'	26°18'	26°18'
Downcoming Rad. (Adj.) (ly. min.⁻¹)	0.760	0.750	0.740	0.539	0.565	0.511	0.455	0.445	0.415
Upcoming Rad. (Adj.) (ly. min.⁻¹)	0.417	0.418	0.420	0.282	0.337	0.297	0.157	0.172	0.175

*ly. (langley) = 1 gm. cal. cm⁻².

data from these runs and the data adjusted for angle of solar elevation are presented in table 2.

In figure 5 the albedo values from the three flights have been plotted according to altitude and filter type, and lines have been drawn through the points to give extrapolated surface values of albedo. The rates of change of albedo with respect to height in each of the two sets of clear filter measurements on November 13 were regarded as having equal significance, even though the rates of change themselves were not alike, and the average albedos measured in the two sets of runs were nearly the same, even though the types and concentrations of ice in them and the average angle of solar elevation in each of them were different. A single straight line (solid) drawn through the combined plot of these two sets of values showed a decrease of albedo of 1.4 percent for each 1,000-ft. rise in altitude above the surface. Along the slightly bent line (dashed) passing through the three values of albedo measured with the red filters on November 15 the albedo decreases approximately 5 percent per 1,000-ft. rise in altitude above the surface. Because the measurements on these days do not establish what variations of albedo with altitude might occur under other conditions, the albedo measurements given in table 1 have not been adjusted to represent surface values.

Many of the data gathered did not lend themselves to easy classification, but they are nevertheless typical of the Antarctic ice environment. These data were arranged in terms of the percent of new and old winter ice in the total view. Such groupings appear in figure 6 for the measurements made under clear sky conditions, and in figure 7 for measurements which include scattered clouds below the aircraft. No differentiation is present in these measurements for various altitudes of the aircraft or for differing solar elevation angles. When such a breakdown was attempted, any differences were apparently overshadowed by variations in the albedo within the chosen category. These groupings would seem to offer a means of assigning albedo values to the large areas of pack ice surrounding the Antarctic continent.
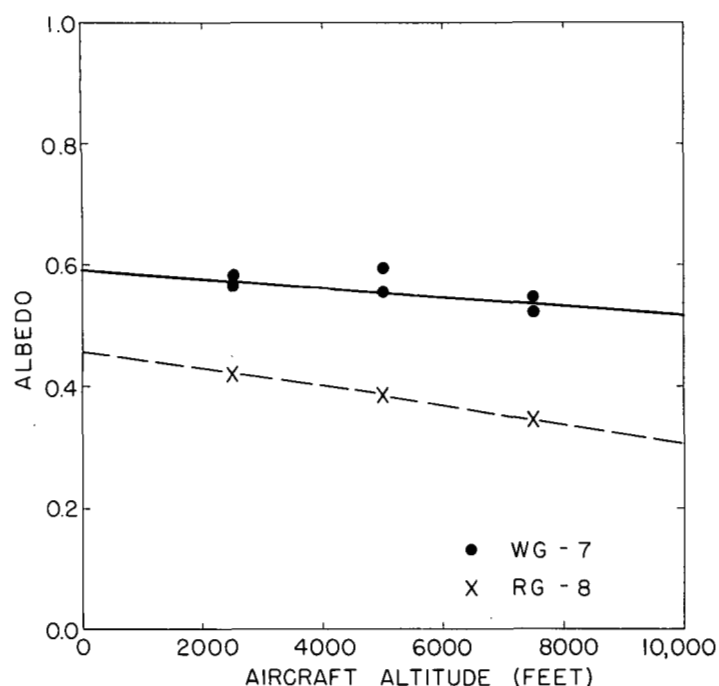
FIGURE 5.—Variation of measured albedo with aircraft altitude under clear sky conditions. The black circles indicate measurements made using WG-7 or clear filters during runs made on November 13, 1962. The crosses indicate measurements made using RG-8 or red filters during runs made on November 15, 1962.
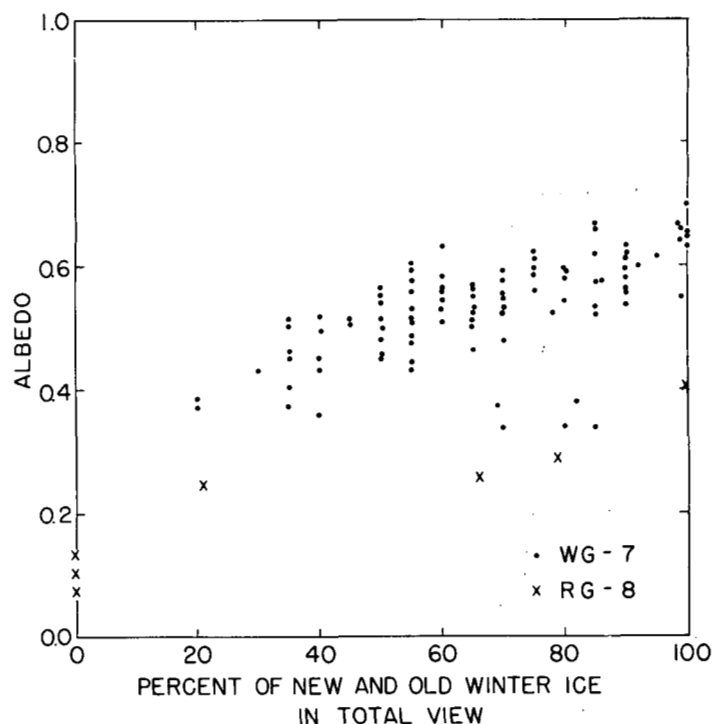

FIGURE 6.—The albedo of sea ice of mixed types and concentrations in terms of the percent of new and old winter ice present under clear sky conditions. Dots indicate WG-7 or clear filter measurements, and crosses indicate RG-8 or red filter measurements. Measurements are not differentiated according to aircraft altitude or angle of solar elevation.

4. DISCUSSION

The Russian airborne measurements near Mirny gave albedo values of winter ice from 0.50 to 0.72, with a mean of 0.65, and gave values over the Shackleton Ice Shelf of 0.51 to 0.78. These compare well with our values over winter ice of 0.60 to 0.70, with a mean of 0.65, and our value over the Ross Ice Shelf of 0.72. These are for clear skies. Hanson [7], in an analysis of radiation data collected in July and August 1958 over Arctic ice islands, derived albedo values for puddled ice based on a value of 0.65 for melting pack ice without puddles. Russian data by Briazgin [4], to whom Hanson also referred, gives this as an average value for winter ice found in the Arctic. Briazgin's range of values for this type extends from 0.58 to 0.70. For melting ice in the Arctic, Briazgin gives an average value of 0.60 with a range from 0.40 to 0.70. It is not known whether all the values given by Briazgin were clear sky measurements or not, but Hanson restricted his determinations to cases for which he had a fair certainty that the values were under overcast skies. Liljequist pointed out on the basis of his measurements at Maudheim that under overcast skies the albedo of snow surfaces is greater because of a relative increase in the visible component of the solar radiation. Whether gray ice or melting ice would exhibit the same characteristics we do
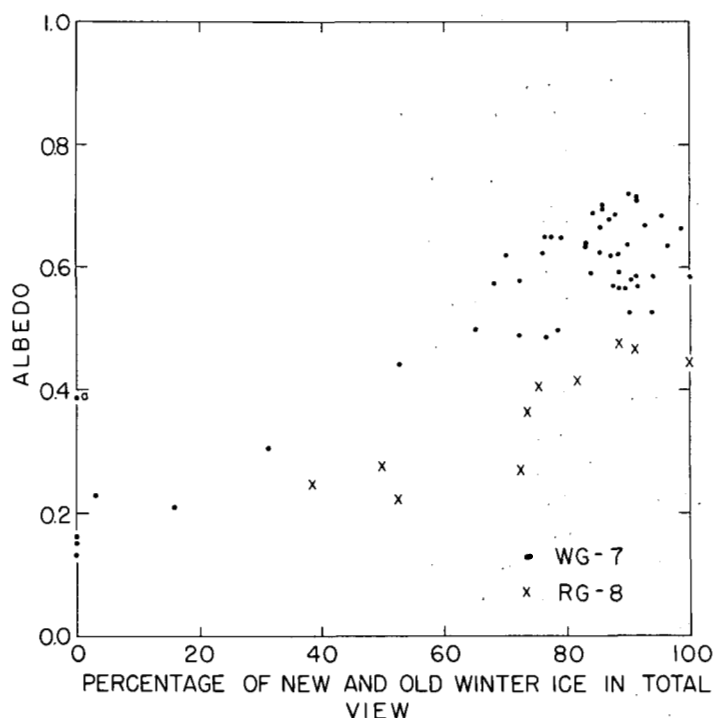

FIGURE 7.—The albedo of sea ice of mixed types and concentrations with scattered clouds between the ice and the aircraft. The dots and crosses indicate the WG-7 and RG-8 filter measurements, respectively.

not know, but the albedos we measured with the RG–8 red filters over various types of ice support Liljequist's findings.

Variations of measured albedo with altitude have already been mentioned, but some additional discussion of this facet of airborne albedo measurement can be made here. Many airborne studies of albedo avoid this problem very nicely by treating only measurements at altitudes low enough that the influence of altitude is negligible. In some ways this should be far less of a problem in the clear dry Antarctic atmosphere than elsewhere. As already pointed out, our measurements of albedo at different altitudes indicated albedo decreasing with increasing altitude; the values measured with clear filters decreased approximately 1.4 percent per 1,000 ft. (the extrapolated surface value would be about 10 percent greater than the value at 7,500 ft.); the values measured with red filters decreased approximately 5 percent per 1,000 ft. (the extrapolated surface value would be about 37 percent greater that the value at 7,500 ft.). Measurements over the United States have shown increasing albedo values with increasing altitude: Fritz [6] found an increase of 1.15 percent per 100 m. or 3.5 percent per 1,000 ft. over Missouri; Hanson and Viebrock [8] assumed an increase of 0.91 percent per 100 m. or 2.8 percent per 1,000 ft. over New Jersey; and Kuhn and Suomi [9] found albedo values over the Midwest to increase approximately 1 percent per 4,000 ft. or 0.25 percent per 1,000 ft. of increase in altitude. The Kuhn and Suomi value just cited was obtained using a pyranometer at the focus of the downfacing parabolic beam reflector beneath an aircraft. On the basis of albedos measured over a sea surface near England, Roach [13] reported rapidly increasing values during the first few thousand feet of ascent. The values leveled off as they approached the computed Rayleigh albedo of the atmosphere through which the measurements were being made. The Russian measurements near Mirny reported by Belov [3] also contain some evidence of increasing albedo with increasing altitude. For example, the following values measured over sea ice were given: 0.69 at 100 m., 0.70 at 2,000 m., and 0.72 at 3,500 m. Counter to these changes, Bauer and Dutton [2] give evidence of albedo measured over snow-covered lake ice during late winter in Wisconsin decreasing with increasing altitude through the first 2,000 ft.

A common derivative it would seem from albedo measurements, especially where data are available at several levels, is the computation of absorbed solar radiation within the layers and perhaps even extrapolated values for the whole atmosphere. Hanson and Viebrock computed a value of 0.285 ly. min.$^{-1}$ in the 402 to 1017-mb. layer, or 0.464×10^{-3} ly. min.$^{-1}$ mb.$^{-1}$, which converts to a temperature change of 0.116° C. hr.$^{-1}$ Fritz determined a value of 0.05° C. hr.$^{-1}$ for the lower 10,000 ft. of the atmosphere over Missouri. The first of these occurred near noon in September; the second during midmorning in March. Roach derived heating rates of

2°–3° C. per day or 0.083°–0.125° C. hr.$^{-1}$ over sea surfaces around noon during the summer. For comparison the following are offered from our measurements on November 13 and 15 for the 7,500–2,500-ft. layers: 0.133×10^{-3} ly. min.$^{-1}$ mb.$^{-1}$ or 0.033° C. hr.$^{-1}$, November 13 (#1); 0.243×10^{-3} ly. min.$^{-1}$ mb.$^{-1}$ or 0.061° C. hr.$^{-1}$, November 13 (#2); and 0.336×10^{-3} ly. min.$^{-1}$ mb.$^{-1}$ or 0.082° C. hr.$^{-1}$ November 15. All of the three heating rates fall within the range of values found by others. The first two values appear somewhat more reasonable than the last one because the last is larger than the first two—indeed, it meets the lower limit found by Roach over a sea surface—even though it is for the sub-spectral band, 0.69–3.5 microns which is included within the band width of the WG–7 filters used for the first two. Furthermore, the first two determinations were made for measurements over partially open water which had warmer temperatures than the solid winter ice over which the measurements for the last determination were made. It is difficult, nevertheless, to determine whether the last actually is more unrealistic than the first two in view of the variation present in the first two values—which might have been greater with more data samples, since most of the absorption of solar radiation in the atmosphere could reasonably occur within the part of the spectrum covered by the RG–8 filters.

Fundamental to a discussion of measured parameters is a consideration of errors likely in the data from which subsequent relationships are determined. Various sources of error can be cited in the case of these albedos. Probably the first that will be encountered is that of the calibration factors of the instruments. Each pyranometer was rather extensively checked for calibration before and after being involved in these measurements. The type of Eppley pyranometer employed is regarded by its manufacturer as having a calibration value known at a given temperature to within 2 percent. The comparison values partly shown in figure 3B vary by 3 percent, but this has been known to reach 10 percent on occasion. Of special consideration in our pyranometer calibrations was the matter of gaging the temperature of the instrument during measurements. As already mentioned this information is gotten from a thermocouple imbedded in the body of the pyranometer and read against the output of a similar thermocouple kept in an ice-water bath. Differences may thus result because of stratification of the temperatures in the ice-water bath and because of a non-uniform temperature distribution within the pyranometer quite apart from differences which might arise from contact potentials in the thermocouple circuitry. Lack of temperature equilibrium between the pyranometer and its environment may be regarded as a serious source of error as it has been our experience in performing calibration tests, wherein the ambient temperature surrounding the pyranometer has been varied over a wide range, that variations in output at a given indicated temperature have resulted. We do not consider it likely that the pyranom-

eters in their field application underwent temperature changes rapid enough to appreciably affect their output reliabilities, but this cannot be ruled out as a source of instrument output variation.

Selection of values of albedo from among those obtained as representative of the type of ice surface beneath the aircraft, especially as this appears in photographs taken directly below, may be subject to errors of several sorts. Among these are: the limited view, a 72° angle about the downward centerline, compared with the hemispheric view of the pyranometers, the duration of flight over a given ice type, and the presence of haze or obscuring matter between the aircraft and the surface below. Since the photographs cannot, even in a connected sequence, fully confirm that the surface below was extensive enough of a selected type to enable the pyranometer to see that and only that type, reliance had to be placed upon visual observation and on the probability that beyond what the observer and the camera were able to see would not materially affect the pyranometer reading. Any judgment as to the duration of a flight over a given ice type for full instrument response rests on the small likelihood that a longer duration flight over the same surface type would have altered the results. Obscurations between the aircraft and the surface below can be noted by the observer and the data considered with that in mind or rejected, or the flight can be made at such a level as to render such interferences negligible. Measurements taken at a lower level would increase the probability of obtaining fewer errors from any of these factors. In our measurements we did not find the time response of the pyranometers, which we had roughly determined to be slightly longer than the 30 sec. indicated by the manufacturer, to be an appreciable factor in adapting to the changing upcoming radiation from the varying surfaces below. The lower pyranometer appeared to respond more nearly to the changing scene below, as indicated in the photographs, than a theoretical consideration of its view would suggest.

The recording digital voltmeter provided another source of data error, especially at low levels of radiation. An additional amplification of ten times would have been helpful in giving better resolution to measurements over areas of low reflectivity when the sun was also low. Digital readout instruments generally produce an uncertainty of one digit in the last place of any reading, a rather large error with very low values. The recorder used for these measurements frequently printed its last significant digit as a 9. This was corrected somewhat by increasing the sensitivity of the meter, but increase in sensitivity resulted in longer balance time for the potentiometer section and consequent loss in area resolution. A compromise had to be reached that would satisfy both accuracy and coverage requirements. Such digital persistances, jumps, and oscillations were usually noticeable in the raw data and have been corrected in the analyses.

Another source of error was traceable to the bearing of the sun relative to the aircraft's heading. In order for the downcoming radiation to be accurately known it must be received on a horizontal surface, since small departures from horizontal in the sensing surface are known to produce sizable errors in the received radiation. Reception of the upcoming radiation by the downfacing pyranometer would not appear to be as sensitive to slight deviations from horizontal in the orientation of the sensing surface. This source of error was not detected until a Fourier analysis of downcoming radiation in terms of solar bearing angle indicated a pattern of maximum and minimum values. Because the instruments could be leveled in flight, presumably making the received downcoming radiation independent of solar bearing, a certain amount of scatter of the data is present along with the harmonic pattern. The effect on the albedo measurements was slight, within the envelop of other errors, but for accurate estimates of the radiation present, downcoming and upcoming, at a given altitude, solar elevation angle, and above a given surface, flight paths should be reversed to cancel pyranometer output variations likely to be attributable to differences of solar bearing.

Other errors in the data may have been caused by the accumulation of contaminants on the filter surfaces of the pyranometers. Although the pyranometers were always clean when installed at some altitude above the ground, they could accumulate an oil film from the engine exhausts or slight amounts of ice from passing through clouds. The latter is known to have occurred in certain instances and suspected in others because of significantly reduced readings when flying directly into the sun, a situation that renders contaminants on the forward side of the pyranometer filters most noticeable. Oil was not found to be consequential.

5. CONCLUSIONS

The albedo of the ring of pack ice around the Antarctic continent can be fairly well estimated from about 0.65 down to 0.10 in terms of its percent of new and old winter ice under clear sky conditions. Further studies have yet to deal with the effects of cloud cover which quickly forms over areas where the ice has broken up. The albedo values found tend to confirm the previous aerial measurements by Russian investigators near Mirny and measurements of pack ice albedo in the Arctic. The ice over which the measurements were made was generally snow covered, although gray wind-swept ice was frequently present. No evidence of puddling as reported in the Arctic was found, although patches of rotten ice were occasionally encountered. Openings between ice floes were soon spanned by a thin ice sheet nearly as dark as the water, but this ice appeared to rapidly acquire a snow cover and to thicken.

Measurements indicated a decrease of albedo with increasing height, but the range of magnitudes of this change

and the apportionment of the effect between atmospheric absorption and atmospheric reflection still remains an unanswered question.

To test the results in the problem raised as to why and how does the "kernlose" winter temperature regime come about will require an extensive application of the albedo data at hand as well as extensive information on the size and concentration of the ice belt through the whole summer season along with the cloud cover present at that time. This problem is now being studied using the data being furnished by polar orbiting satellites.

ACKNOWLEDGMENT

REFERENCES

1. A. K. Ångström and A. J. Drummond, "Basic Concepts Concerning Cutoff Glass Filters Used in Radiation Measurements," *Journal of Meteorology*, vol. 18, No. 3, June 1961, pp. 360–367.
2. K. G. Bauer and J. A. Dutton, "Albedo Variations Measured from an Airplane over Several Types of Surfaces," *Journal of Geophysical Research*, vol. 67, No. 6, June 1962, pp. 2367–2376.
3. V. F. Belov, "Al'bedo podstilaiuscheǐ poverkhnosti i nekotorykh form oblakov v raǐone Antarkticheskogo sklona i moriâ Deǐvisa," [Albedo of the Underlying Surface and of Some Forms of Clouds in the Region of the Antarctic Slope and the Davis Sea], *Trudy*, Tsentral'naiâ Aerologicheskaiâ Observatoriiâ, No. 37, Moscow, 1960, pp. 55–58. (English translation by Irene A. Donehoo, Foreign Area Section, Office of Climatology, U.S. Weather Bureau.)
4. N. N. Briazgin, "K voprosu ob al'bedo poverkhnosti dreifuiushchikh l'dov," [The Problem of the Albedo on the Surface of Drifting Ice], *Problemy Arktiki i Antarktiki*, No. 1, Leningrad 1959, pp. 33–39. (English translation for Geophysics Research Directorate, Air Force Research Division, by American Meteorological Society, on Contract No. AF 19(604)–6113, by Richard M. Holden, translator.)
5. Eppley Laboratories, "Transmission Data and Filter Factors for Schott WG–7, RG–2, and RG–8 Glasses Determined at the Eppley Laboratory for the U.S. Weather Bureau," (Unpublished document.) [Copies available from the authors on request.]
6. S. Fritz, "The Albedo of the Ground and Atmosphere," *Bulletin of the American Meteorological Society*, vol. 29, No. 6, June 1948, pp. 303–312.
7. K. J. Hanson, "The Albedo of Sea-Ice Islands in the Arctic Ocean Basin," *Arctic*, Journal of the Arctic Institute of North America, vol. 14, No. 3, Sept. 1961, pp. 188–196.
8. K. J. Hanson and H. J. Viebrock, "Albedo Measurements over the Northeastern United States," *Monthly Weather Review*, vol. 92, No. 5, May 1964, pp. 223–234.
9. P. M. Kuhn and V. E. Suomi, "Airborne Observations of Albedo with a Beam Reflector," *Journal of Meteorology*, vol. 15, No. 2, Apr. 1958, pp. 172–174.
10. G. H. Liljequist, "Energy Exchange of an Antarctic Snow-Field, Short-Wave Radiation," *Norwegian-British-Sweden Antarctic Expedition, 1949–52, Scientific Results*, vol. II, Part 1A, Norsk Polarinstitutt, Oslo, 1956, 109 pp.
11. K. S. Lyubomirova, "Zavisimost' al'bedo l'da ot ugla padeniiâ solnechnykh lucheǐ," [Dependence of Ice Albedo on Incidence Angle of Solar Rays , *Meteorologiiâ i Gidrologiiâ*, No. 8, July 1962, pp. 28–31. (English translation by Lloyd G. Robbins, issued by American Geophysical Union in *Soviet Hydrology*, Feb. 1963, pp. 124–128.)
12. R. M. Marchgraber and A. J. Drummond, "A Precision Radiometer for the Measurement of Total Radiation in Selected Spectral Bands," Contributions to the International Radiation Symposium IAMAP, Oxford 1959, *IUGG Monograph* No. 4.
13. W. T. Roach, "Some Aircraft Observations of Fluxes of Solar Radiation in the Atmosphere," *Quarterly Journal of the Royal Meteorological Society*, vol. 87, 1961, pp. 346-363.
14. A. F. Spano, "Results of an Airborne Albedo Program in Antarctica, 1963," *Monthly Weather Review*, vol. 93, No. 11, Nov. 1965, pp. 697–703.
15. U.S. Army Electronic Proving Ground, Technical Memorandum USAEPG–SIG 970–38, *Procedure for Installation and Use of the Eppley Radiometer (Selective Band Pyranometer)*, Task 64–0001, Fort Huachuca, Ariz. Oct. 1960. 12 pp.
16. H. Wexler, "The 'Kernlose' Winter in Antarctica," *Geophysica*, vol. 6, No. 3-4, 1958, pp. 577–595.